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Numerical Simulation of the Cervical Spine in a Normal Subject and a Patient with Intervertebral Cage under Various Loadings and in Various Positions

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ABSTRACT

Background: Cervical spine sustains most of the vertebral column injuries, among other injuries, the disc degeneration and damage that lead to replacement of the damaged disc with cage or artificial disc.
Methods: The C4 to C6 vertebrae of a normal subject and a person with interbody fusion cage were 3d modelled and then analyzed using Finite element method. The results of maximum stress and strain in cervical spine of the normal subject and patient were compared in three positions: standing, lying with axial rotation of neck and standing with axial rotation of neck.
Results: The maximum principal strain and stress in the patient are respectively 10.5% and 14.5% greater than those in normal subject in standing position, however in lying position when the head has axial rotation, the maximum principal strain and stress are in the normal subject 6.2% and 16.3% greater than those in patient, respectively. The difference between these results and the results of strain and stress in standing position when the head has axial rotation is very small. This outcome is due to smallness of the stress exerted on cervical spine as a result of the head weight (131-150 Pa).
Conclusion: In contrary to the constraint between disc and vertebrae, there is no friction between cage and vertebrae and this leads to maximum stress transfer to the first vertebra above the cage in patient. However, the maximum stress is ultimately less in the patient with fusion cage than the normal subject. Generally, only the neck rotations are the cause of cervical spine injury in normal neck movements.

Keyword: Cervical spine; Axial rotation; Principal strain; Stress; Vertebra; Fusion cage

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INTRODUCTION

The cervical region is the most common location of vertebral column injuries [1]. The cervical spine, which consists of 7 vertebrae (C1-C7), supports the head weight and makes a wide range of movement for head possible [2]. The vertebral bone is of a sandwich structure consisting of a stiff outer shell, the cortical bone, a porous inner marrow, and the trabecular bone [3,4]. Disc has two parts: the inner part (nucleus pulposus) and the outer part (annulus fibrosus) [4]. According the report of the US insurance agency, the cost spent in 2007 for cervical spine related diseases was about 8.8 billion dollars equaling to 25% of the total sum paid for all injuries due to accidents [5]. Therefore studying the injuries and problems of the cervical vertebrae is hence of great importance.

Part or all of the cervical vertebrae of a normal person have been analyzed using Finite element method (FEM) in a group of previous studies. Teo et al. and Graham et al. modeled the whole C2 vertebra of a normal person three-dimensionally and simulated it using FEM in 1994in order to study the odontoid fracture [6,7]. Ng et al. and Tan et al. analyzed a non-linear model of a number of cervical vertebrae under axial compressive load using FEM [8,9]. Zhang et al. analyzed a 3d non-linear model of cervical vertebrae and skull of a normal subject under torsional loading and simulated the movements of head and cervical spine under flexion, extension, axial rotation and lateral bending [10]. None of these studies, however, analyzed the case in which the cervical intervertebral disc had been replaced with an artificial disc or cage due to disease. They investigated merely the conditions of subjects with normal discs.

Chiang et al. analyzed a 3d model of C4-C6 vertebrae with a fusion cage using FEM and investigated the effect of cage material on the rotational movement of the neck [11]. Some studies used FEM to investigate the effect of the range of motion in patients with artificial disc [12,13]. Further, some studies used numerical simulation to compare the effect of artificial disc type on the quality of neck movement performance [14-16]. Lin CYet al. used the CT scan images to build a 3d model of the cervical vertebrae C3 to C7 of a normal subject and then calculated the cervical total disc stress and displacement after implantation surgery at the C5-C6 level using FEM analysis. They also calculated the instantaneous center of rotation and facet joint force in various types of artificial discs and compared them with each other [17]. In a recent study, Lee JH modeled the C2-C7 vertebrae, analyzed the model using FEM and evaluated the effect of changing the material and location of the artificial disc on the manner of changes in mechanical parameters affecting the disc [18].

Another group of studies made no use of numerical analysis but measured mainly the deformation of an artificial disc using clinical data. Jaumard et al. measured the C5-C6 facet pressure diagrams from seven osteoligamentous vertebrae C2-T1 of a cadaver using a transducer. They inserted then an implant and calculated the maximum deformation on the implant, after a lateral bending and axial rotation and compared to the maximum deformation on the normal disc of healthy subject [19].Chen et al. examined 80 patients treated with artificial discs made of two different materials (PEEK and titanium). They also compared the Neck Disability Index in two groups of patients. They reported that this index indicated more appropriate and desired outcomes in patients treated with artificial discs made of PEEK [20].

As seen, most of the previous studies examined those patients who had a damaged disc replaced with an artificial disc. The present study models the C4-C6 vertebrae three-dimensionally and analyzes the effects of axial rotation and head weight in lying and standing positions using FEM. It also compares the strength and the deformation of cervical vertebrae and discs in a normal subject and a patient with fusion cage.

MATERIALS AND METHODS

According to previous studies, most of the problems and diseases of cervical vertebrae occur in discs between C4-C5 and C5-C6 joints [1,3]. Therefore in the present study, first the 3d model of C4-C6 vertebrae was produced in solid works 2016 SP2 using the general dimensions presented in table 1 for the vertebrae, discs and cage bodies. The model was transferred then to ABAQUS version 6.14-2 for meshing and analysis. It is noteworthy that the results were extracted for two subjects in three separate states: in standing position when the cervical vertebrae support merely the head weight, in lying position when the head weight isn't exerted on the vertebral column but the neck is axial rotating, and in standing position when the cervical vertebrae support the head weight and neck is axial rotating too. Finally, the results of the two subjects – a normal subject with healthy vertebrae and discs in the cervical spine and a patient having a cage with three triangular holes between the vertebrae C5 and C6 were compared with each other.

PEEK is according to the study by Chiang et al. the most appropriate material for cage [11,20]. So the mechanical properties of the PEEK cage, as seen in table 2, were used

Table 2. Material properties of vertebrae, discs and cage.

Poison ratio	Module of elasticity (MPa)	Component
0.3	1.0×104	Vertebrae
0.3	4.2	Disc
0.2	1.3×103	PEEK polymer cage

Table 1. The general dimensions of vertebrae, discs and cage body

Disc/cage (mm)	C6 (mm)	C5 (mm)	C4 (mm)	Vertebral body
25	25	25	25	diameter
7	15	15	15	height

for the analysis in the present study [11]. It is noteworthy that in the present study, similar to the study by Teo et al., the vertebrae were considered to be homogenous and completely cortical [6] and the nucleus pulposus part was ignored in the disc model. The biomechanical properties of the disc and vertebra have been presented in table 2 [21].

Merely the cervical vertebrae were analyzed in the present study and the thoracic and lumbar vertebrae were not analyzed. So similar to the study by Zhang et al., the lower part of vertebrae in the lower surface of C6 were fully constrained [11]. The constraint between the cage and vertebra was considered to be frictionless and to have tied [21,22].

To simulate the head weight on the vertebral column, a 73.6-N distributed compressive force was exerted on the C4. Similar to the study by Moroney et al., a torqueof 1.8 N.m was applied to the upper surface of C4 vertebra about the axial axis to simulate the axial rotation of head [23,24].

The convergence of responses was examined in the next step. The hexdominant element was used for meshing the discs and vertebrae in the patient and the normal subject and the tetrahedral element was used for meshing the patient's cage. The total number of elements used for meshing the cervical vertebrae and discs was 14190. The results were computed for a time step of 0.01. The mesh independence study was done according to Figure 1. Figure 1 shows that the maximum difference between the data of maximum stress in medium and fine meshes of the normal subject is less than 0.2%. This value is 0.32% for the patient. So the convergence of responses and the results independence from the meshing conditions have been acceptably ensured.

RESULTS

Two indices of stress and deformation were used in the present study for evaluating and comparing the biomechanical properties of the cervical spine in patient and normal subject. The principal strain was used for expressing the amount of deformation in disc and vertebra and the criteria of Von Mises stress was used for investigating the stress.

Standing position

First a position is examined in which the subject is standing without neck rotation and only the head weight is applied to the cervical spine. The results are computed for both the normal subject and patient and are compared with each other. A distributed compressive load of 73.6 N is applied as the head weight to the cervical spine of the normal subject and the patient with cage and the conditions of both subjects are compared in order to evaluate the effectiveness of the disc replacement with cage.

Strain evaluation

According to Figure 2, the maximum principal strain in the normal subject and the patient is 7.6x10^{-6} and 8.4x10^{-6}, respectively. So the principal strain in the patient is 10.5% greater than that in the normal subject. The location of the maximum strain in the normal subject is in all discs while in the patient, it is transferred to the first disc above the cage ($C_{4/5}$). This means that although the strain in the first disc above the cage (C5) in the patient is greater than the strain in discs under and above the C5 vertebra of the normal subject, the strain in cage itself is very small and in an acceptable range.

Stress evaluation

According to Figure 3, the maximum stress in the normal subject and the patient is 131 and 150 Pa, respectively. So the maximum stress in the patient is 14.5% greater than that in the normal subject. The location of the maximum stress in the normal subject

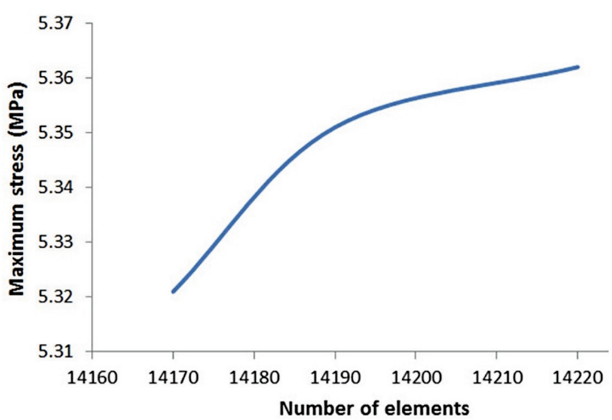

Figure 1. Panel shows the mesh independence study for normal subject.

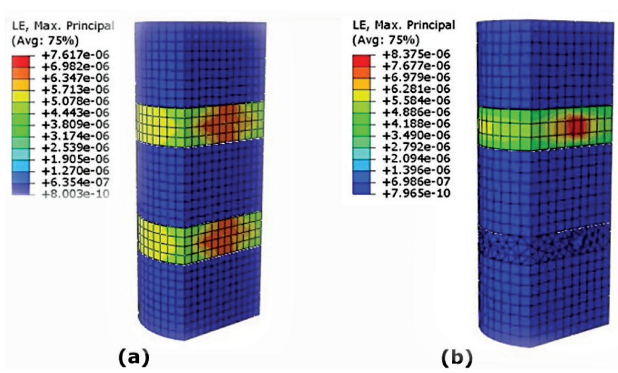

Figure 2. (a) and (b) show principal strain in the cervical spine of normal subject and patient for standing position, respectively.

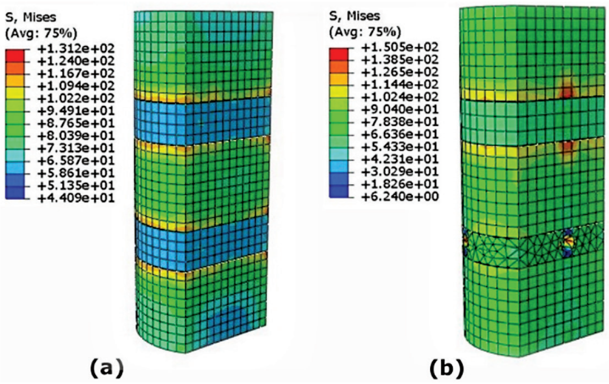

Figure 3. (a) and (b) show normal stress in the cervical spine of normal subject and patient for standing position, respectively.

is in all vertebrae where the vertebra attaches to the disc while in the patient, it is transferred to the vertebra above the cage but still at the same place where vertebra attaches to disc.

Lying position

In this part, a position is examined in which the subject is lying so that the cervical spine doesn't support the head weight and simultaneously the neck experiences an axial rotation. Therefore the effect of axial rotation on the cervical vertebrae in lying position is simulated. A torque of 1.8 N.m is exerted about the axial axis of the cervical spine to simulate axial rotation. Finally, the results of the patient and the normal subject are compared in order to evaluate the effectiveness of the disc replacement with cage.

Strain evaluation

According to Figure 4, the maximum principal strain in the normal subject and the patient is $3.28x10^{-1}$ and $3.09x10^{-1}$, respectively. So the principal strain in the normal subject is 6.2% greater than that in the patient. The location of the maximum strain in the normal subject is same as before in all discs while in the patient, it is transferred to the first disc above the cage.

Stress evaluation

According to Figure5, the maximum stress in the normal subject and the patient is 5.34 and 4.59 MPa respectively and occurs only in C5 vertebra in both subjects. Therefore in contrary to the standing position, the maximum stress hereis in the normal subject 16.3% greater than that in the patient with fusion cage. As seen, there is a great difference between the results of this section and those of the section 3.1.2 regarding to both the stress amount and location.

Standing position with neck rotation around the axial axis

The most common loading of cervical spine occurs at the time when an individual is standing and rotates his neck around the axial axis. In such a case, a torque of 1.8 N.m (equivalent to the axial rotation) acts in addition to the compressive force due to the head weight (73.6 N) on the cervical spine. In fact, a combined loading, which simulates the axial rotation of the neck in standing position, is exerted in the cervical spine. Again, the effectiveness of the disc replacement with cage is evaluated by comparing the results obtained for the normal subject and the patient.

Strain evaluation

According to Figure 6, the maximum principal strain in the normal subject and the patient is $3.31x10^{-1}$ and $3.18x10^{-1}$, respectively. So the principal strain in the normal subject is 4% greater than that in the patient. The location of the maximum strain in the normal subject is same as previous positions in all discs while in the

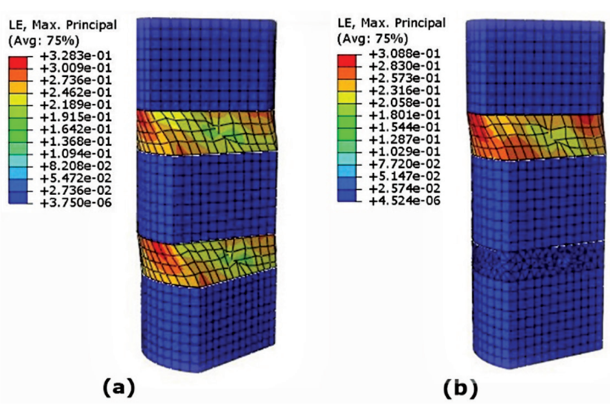

Figure 4. (a) and (b) show principal strain in the cervical spine of normal subject and patient for lying position, respectively.

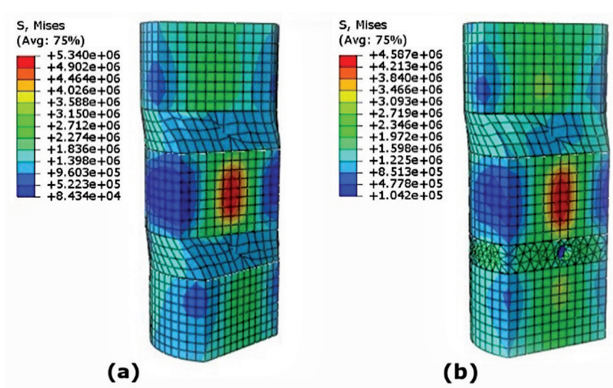

Figure 5. (a) and (b) show normal stress in the cervical spine of normal subject and patient for lying position, respectively.

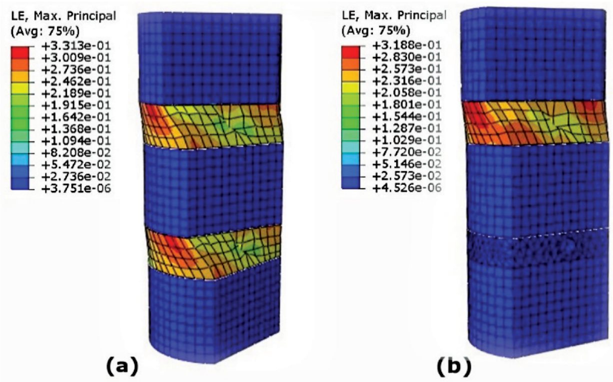

Figure 6. (a) and (b) show principal strain in the cervical spine of normal subject and patient for standing position with neck rotation, respectively.

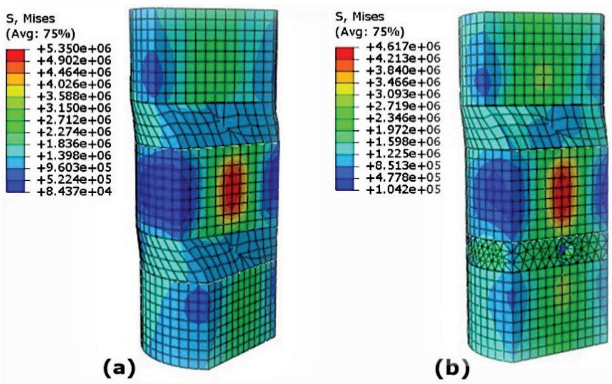

Figure 7. (a) and (b) show normal stress in the cervical spine of normal subject and patient for standing position with neck rotation, respectively.

patient, it is in the $C_{4/5}$ intervertebral disc.

Stress evaluation

According to Figure 7, the maximum stress in the normal subject and the patient is 5.35 and 4.61 MPa respectively and its location is similar to the section 3.2.2. This results agrees completely with the results reported in the study by Chiang and colleagues [11]. Therefore the maximum stress in the patient after replacement of the disc with cage has reduced16.1% and cage has led to stress reduction.

DISCUSSION

The criterion of Von Mises stress is used for evaluating the strength of vertebras, discs and cage while the principal strain for evaluation of deformations was calculated by software in the present study.

Comparing the standing position with the lying position accompanied by neck rotation

The results of section 3.1 show that the maximum principal strain in standing position when the cervical spine supports only the head weight is 10.5% greater in patient than the normal subject. The reason of increase in strain and transfer of the maximum strain location to the first disc above the cage can be explained by investigating the module of elasticity of vertebrae, discs and cage in table 2. According to table 2, the strength of vertebrae is 2381 times of the discs strength. Therefore the maximum strain in normal subject occurs in discs and not in vertebrae. Since the cage is 309.5 times stronger than the disc, the location of maximum strain in the patient with fusion cage is transferred to the disc above the cage ($C_{4/5}$). Therefore due to the greater strength of the cage, the vertebra above the cage (C5) may experience deformation and degeneration with the time. Its possibility is however less than the similar incident in discs of the normal subject's cervical spine. In a similar manner, this analysis can be extended to the stress state between two subjects. It should be noted that the stress in cage holes in standing position is significant according to Figure 3 and its reason is the stress concentration in the holes made in the cage.

Based on the hook's law, the results of stress and strain are proportional. So by evaluating both parameters of stress and strain in standing position (section 3.1), it can be deduced when the cervical spine supports only the head weight, the strain and consequently the deformation due to the head weight is greater in patient than the normal subject and the using the cage in this case is apparently less effective. In general, the maximum stress created in the cervical spine by the compressive force due to the head weight (73.6 N) is so small (131-150 Pa) that being a little weaker has no significant effect on the performance quality and effectiveness of the cage.

As shown in section 3.2, the cervical spine doesn't support the head weight when the subject is lying and the neck has an axial rotation. The amounts of the maximum stress and strain in this case are much greater than those in the standing position and furthermore, the amounts of strain and stress in the normal subject are 6.2% and 16.3% greater than those in the patient with fusion cage, respectively. Therefore fusion cage has caused the stress applied to the vertebra to decrease in this case. It can be claimed based on this argument that the fusion cage has raised the efficiency of the cervical spine in pure rotation.

Comparing the standing position accompanied by neck rotation with previous positions

When the subject is standing and the head has axial rotation, the amount of increase in principal strain in the normal subject with respect to the patient is less than that in the previous positions. After disease appearance and replacement of disc with cage, the maximum stress applied to cervical spine decreases 16.1% according to the results of section 3.3.2. So the fusion cage has increased the efficiency in simultaneous compressive and torsional loading.

The location of the maximum stress in patient has been transferred to C5 vertebra and its reason is the boundary conditions of the problem. The constraint between C5 and cage is frictionless, i.e. in contrary to the conditions of a normal disc, there is no friction between C5 and cage, so a smaller part of the stress applied to cervical spine is transferred to C5 vertebra and in fact, stress is transferred due to the high strength of the cage. When the cervical spine, however, supports merely the head weight and only a compressive force is applied to it, the lack of friction between cage and C5 has no effect on the stress amount since there is vertical loading and the whole stress is transferred directly to disc or cage in both boundary conditions.

Results show that the difference of maximum stress and strain between patient and normal subject can be ignored in lying position when the subject is only under axial loading and in standing position when the subject undergoes both axial loading and compressive loading due to the head weight. Because of the great amount of stress due to axial loading (4.50-5.34 MPa) during the axial rotation of neck, the weight of head has a very small effect on the stress and strain applied to the cervical spine.

The maximum stress and strain applied to the C5 of the normal subject during combined loading is respectively 40701 and 43157 times the pure compressive loading. These values are respectively 30478 and 36785 in fusion cage. Considering the small difference between pure torsional loading and combined loading, it can be concluded that the cervical spine will be more vulnerable to injury when the torsional load is added to the compressive force applied to neck. In fact, the main reason of the cervical spine injuries is neck rotations. Also considering the location where the maximum stress occurs in figures 3, 5 and 7, the effect of stress concentration in cage holes is only in pure compressive loading significant and this effect can be ignored in cases of torsional loading and combined loading.

CONCLUSION

Simulation of the cervical spine in a normal subject and a patient with fusion cage showed that the cage has a more effective performance than the disc of a normal subject in lying position when the cervical spine is only under pure axial rotation loading. The results of the combined axial rotation and compressive loadings which simulate the axial rotation of the neck of a person in standing position confirm to the results of position under pure axial rotation. So the effect of the compressive force on the amount of maximum stress and strain applied to the cervical spine is insignificant. In general the axial rotation of neck and inducing a torsional loading in cervical spine is the main cause of cervical spine injuries.

REFERENCES

1. Zafarparandeh I, Erbulut DU, Lazoglu I, Ozer AF. Development of a finite element model of the human cervical spine. Turkish neurosurgery. 2013 Dec;24(3):312-8.
2. Daniels JM, editor. Common Musculoskeletal Problems: A Handbook. Springer; 2015 Apr 4.
3. Hayashi K. Clinical anatomy of the cervical spine. In Cervical Spondylosis And Similar Disorders 1998 Sep 21 (pp. 15-32).
4. Brolin K. Cervical Spine Injuries-Numerical Analyses and Statistical Survey, 2002.
5. Zhou SW, Guo LX, Zhang SQ, Tang CY. Study on cervical spine injuries in vehicle side impact. Open Mech Eng J. 2010 Feb;4:29-35.
6. Teo EC, Paul JP, Evans JH. Finite element stress analysis of a cadaver second cervical vertebra. Medical and Biological Engineering and Computing. 1994 Mar;32(2):236-8.
7. Graham RS, Oberlander EK, Stewart JE, Griffiths DJ. Validation and use of a finite element model of C-2 for determination of stress and fracture patterns of anterior odontoid loads. Journal of Neurosurgery: Spine. 2000 Jul;93(1):117-25.
8. Ng HW, Teo EC. Nonlinear finite-element analysis of the lower cervical spine (C4–C6) under axial loading. Journal of Spinal Disorders & Techniques. 2001 Jun 1;14(3):201-10.
9. Tan KW, Lee VS, Teo EC, Zhang QH, Ng HW, Seng KY. A C2-C3 finite element model to determine the stress patterns of odontoid loads. In Summer Bioengineering Conference, Florida 2003.
10. Zhang QH, Teo EC, Ng HW, Lee VS. Finite element analysis of moment-rotation relationships for human cervical spine. Journal of biomechanics. 2006 Dec 31;39(1):189-93.
11. Chiang MF, Teng JM, Huang CH, Cheng CK, Chen CS, Chang TK, Chao SH. Finite element analysis of cage subsidence in cervical interbody fusion. Journal of Medical and Biological Engineering. 2004 Dec 1;24(4):201-8.
12. Chang UK, Kim DH, Lee MC, Willenberg R, Kim SH, Lim J. Range of motion change after cervical arthroplasty with ProDisc-C and prestige artificial discs compared with anterior cervical discectomy and fusion.
13. Womack W, Leahy PD, Patel VV, Puttlitz CM. Finite element modeling of kinematic and load transmission alterations

due to cervical intervertebral disc replacement. Spine. 2011 Aug 1;36(17):E1126-33.

14. Denozière G, Ku DN. Biomechanical comparison between fusion of two vertebrae and implantation of an artificial intervertebral disc. Journal of biomechanics. 2006 Dec 31;39(4):766-75.
15. Gandhi AA. Biomechanical analysis of the cervical spine following total disc arthroplasty: an experimental and finite element investigation. 2012.
16. Yang SW, Chien YY, Chen MH. Change of Mobility and Stress Morphology due to Different Types of Artificial Cervical Spine Implementation: a Finite Element Analysis. InProceedings of the World Congress on Engineering 2014 (Vol. 2).
17. Lin CY, Chuang SY, Chiang CJ, Tsuang YH, Chen WP. Finite element analysis of cervical spine with different constrained types of total disc replacement. Journal of Mechanics in Medicine and Biology. 2014 Jun;14(03):1450038.
18. Lee JH, Park WM, Kim YH, Jahng TA. A biomechanical analysis of an artificial disc with a shock-absorbing core property by using whole-cervical spine finite element analysis. Spine (Phila Pa 1976). 2016 Aug 1;41(15):E893-901.
19. Jaumard NV, Bauman JA, Guarino BB, Gokhale AJ, Lipschutz DE, Weisshaar CL, et al. ProDisc cervical arthroplasty does not alter facet joint contact pressure during lateral bending or axial torsion. Spine. 2013 Jan 15;38(2):E84-93.
20. Chen Y, Wang X, Lu X, Yang L, Yang H, Yuan W, Chen D. Comparison of titanium and polyetheretherketone (PEEK) cages in the surgical treatment of multilevel cervical spondylotic myelopathy: a prospective, randomized, control study with over 7-year follow-up. European Spine Journal. 2013 Jul 1;22(7):1539-46.
21. Bahramshahi N. Finite Element Analysis of middle cervical spine. Theses and Dissertations, Paper. 2007;966.
22. Nishida N, Kato Y, Imajo Y, Kawano S, Taguchi T. Biomechanical analysis of cervical spondylotic myelopathy: the influence of dynamic factors and morphometry of the spinal cord. The journal of spinal cord medicine. 2012 Jul 1;35(4):256-61.
23. Moroney SP, Schultz AB, Miller JA. Analysis and measurement of neck loads. Journal of Orthopaedic Research. 1988 Sep 1;6(5):713-20.
24. Moroney SP, Schultz AB, Miller JA, Andersson GB. Load-displacement properties of lower cervical spine motion segments. Journal of biomechanics. 1988 Dec 31;21(9):769-79.